Virtual Laboratory for Technology Input to Budget Planning Meeting

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Gaithersburg, Maryland
March 14, 2007

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Virtual Laboratory for Technology
For Fusion Energy Science

Outline

- VLT Mission, Organization

- Overview of FY07/08 Budget Situation

- For each element
  - Highlights of technical accomplishments
  - FY08 tasks and funding
  - FY09 tasks and funding (-10%, +2% and Full Use cases)

- Special Issues
  - Impacts of reduced technology budgets in the ITER era

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The Enabling Technology Research Mission

To contribute to the national science and technology base by 1) developing the enabling technology for existing and next-step experimental devices, by 2) exploring and understanding key materials and technology feasibility issues for attractive fusion power sources, by 3) conducting advanced design studies that integrate the wealth of our understanding to guide R&D priorities and by developing design solutions for next-step and future devices.

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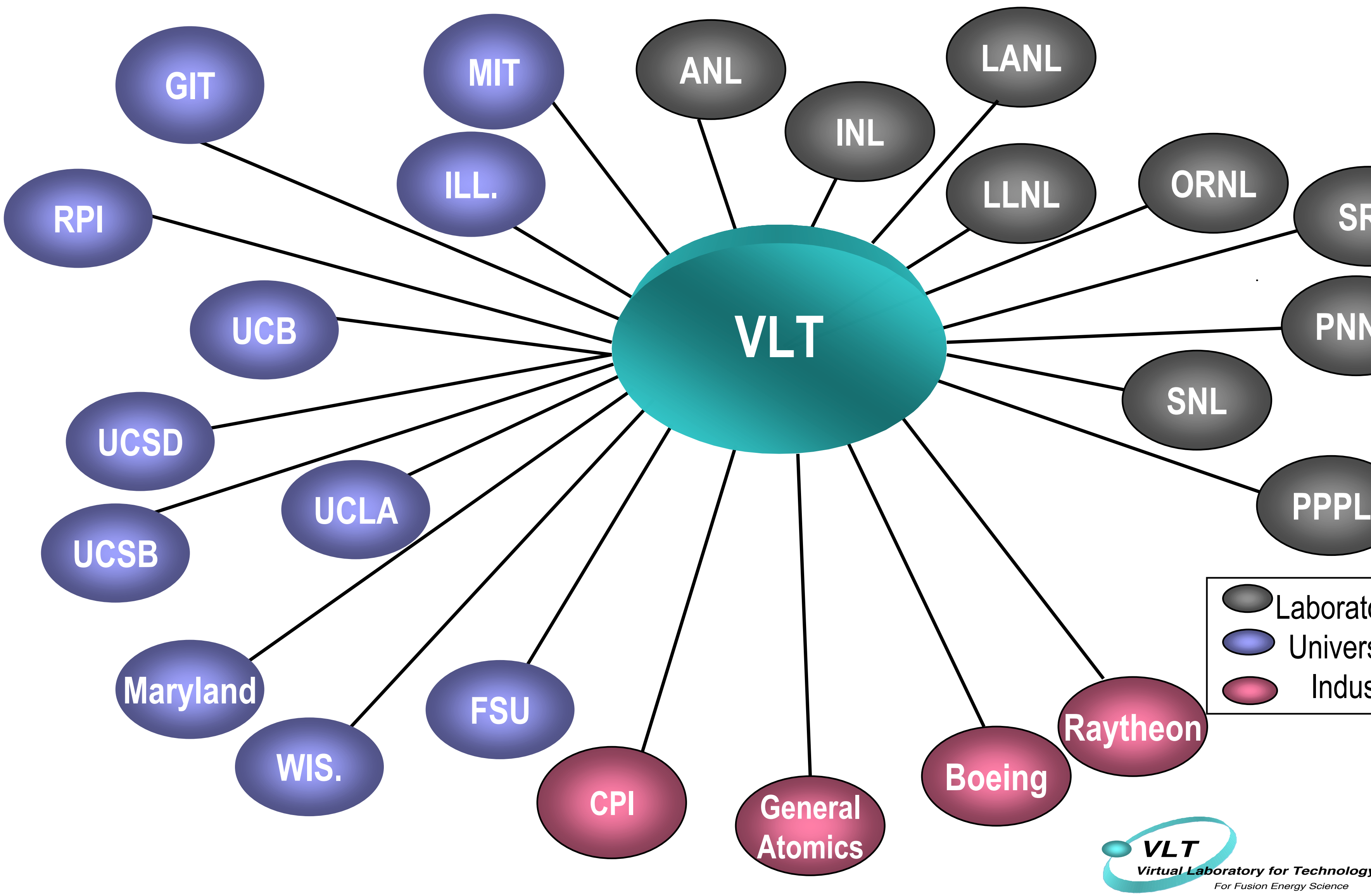
The Technology Program is a Multi-institutional National Resource



VLT Program Element Leaders

Deputy Director	**D.Petti, INL**
<u>Program Element</u>	**<u>Element Leader</u>**
Magnets	**J. Minervini - *MIT***
PFC	**M. Ulrickson - *SNL***
Chamber	**M. Abdou - *UCLA***
ICH	**D. Rasmussen - *ORNL***
ECH	**R. Temkin - *MIT***
Fueling	**S. Combs - *ORNL***
Safety & Tritium Research	**D. Petti - *INL***
Tritium Processing	**S. Willms - *LANL***
NSO/FIRE	**TBD**
ARIES	**F. Najmabadi - *UCSD***
Socio-Economic	**L Grisham - *PPPL***
Materials	**R. Kurtz – *PNNL***

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FY08/09 Budget Considerations

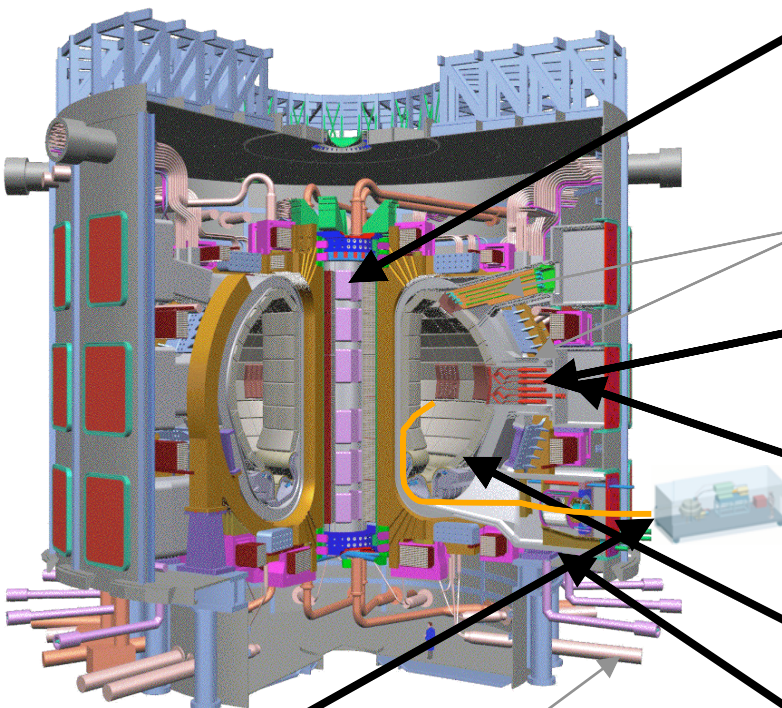
- “In planning for the FY 2009 institutions should increase their focus on burning plasmas and identify specific tasks, such as high-priority International Tokamak Physics Activity (ITPA) R&D, theory, and technology R&D for heating, current drive,diagnostics, etc. The results of such research will be relevant to the fusion program, including ITER.”
  This is the major factor in planning the VLT program.

- “Regarding FY2009 funding for the U.S. contributions to the ITER project, the U. S. ITER Project Office will be responsible for preparing a funding plan for the BPM.”
  Ned Sauthoff to cover work performed by VLT performers in ITER MIE

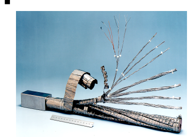
- FY08 Congressional request increases by 3% relative to FY07 Congressional request
  Plasma Technologies increases by 3.9%
  Materials Science increases by 2.7%

- Overall budget is 28% below the FY 05 level

VLT participants led the planning activities and participate in R&D and design for 7 of the U. S. hardware packages



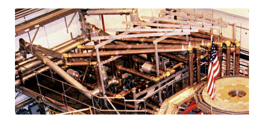
7 Central solenoid windings
8% of TF conductor



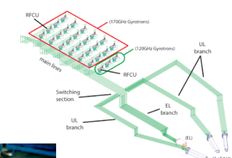
Steady-state power supplies

15% of port-based diagnostic packages

All Ion Cyclroton transmission lines (20MW)



All ECH transmission lines (24MW)



Blanket/shield 20%; limiters

Pellet injector

75% cooling for divertor, vacuum vessel, …

Roughing pumps, standard components

Tokamak exhaust processing system

Cross cutting activities: Materials science, nuclear analysis, safety, Design Working Groups

The VLT is actively involved in USBPO activities (3 members on the Council, Fusion Engineering Science TG lead, Assistant Director for ITER Liason, and physics tasks)

- Active coil system for ELM suppression and RWM stabilization
- ITER disruption mitigation system design and physics understanding
- Tritium retention and H/D/T control
- Requirements for stabilization of (3,2) and (2,1) NTMs
- Limitations to startup flexibility for advanced scenarios
- ELM mitigation
- ICRF antenna performance and coupling studies
- Critical assessment of heating and current drive mix on ITER and impact on achievable scenarios
- Review measurement requirements related to US diagnostic packages
- Evaluate the feasibility of lost and confined fast ion diagnostic systems for ITER
- ITER CODAC architecture design
- ICRF heating and current drive scenarios (time-independent)
- Development of improved pedestal and L-H transition predictive capabilities and impact on ITER design and performance
- Locked-modes and error field correction specification

FY08 Enabling R&D Program Budget ($K) 2/7/07							
B&R	**Program Area**	**Program Elements**	**OFES PM**	FY 05	FY 06 FEB	FY 07 CONG	**FY 08 CONG**
AT6010301	Plasma Technologies	Plasma Facing Components	Nardella	6932	5655	5625	5619
AT6010301	Plasma Technologies	Magnet Systems	Sullivan	2243	1137	90	500
AT6010301	Plasma Technologies	Plasma Chamber Systems	Nardella	1690	1620	1640	1700
AT6010301	Plasma Technologies	ICH Systems	George	1708	1360	1570	1570
AT6010301	Plasma Technologies	Safety and Environment	Nardella	1727	1643	1675	1528
AT6010301	Plasma Technologies	ECH Systems	George	1415	926	546	796
AT6010301	Plasma Technologies	Fueling Systems	George	1022	750	775	775
AT6010301	Plasma Technologies	Tritium Systems	Nardella	934	654	654	654
AT6010301	Plasma Technologies	Neutronics	Nardella	516	435	320	310
AT6010301	Plasma Technologies	Neutral Beam Systems	George	60	50	50	0
AT6010301	Plasma Technologies	IFE Closeout Costs	Nardella	156	0	0	0
AT6010301	Plasma Technologies	Taxes	Nardella	0	0	0	0
	Plasma Technologies	**TOTAL**		**18403**	**14230**	**12945**	**13452**
AT6010501	Advanced Design	Next Step Option-FIRE	Bolton	431	0	0	0
AT6010502	Advanced Design	IFE System Studies	Opdenaker	0	0	0	0
AT6010501	Advanced Design	MFE System Studies	Opdenaker	1686	1643	1716	1716
AT6010501	Advanced Design	VLT Management	Nardella	696	701	744	744
AT6010501	Advanced Design	Socio-economic Studies	Opdenaker	80	80	50	50
AT6010501	Advanced Design	Burning Plasma Applications	Bolton	86	40	40	40
AT6010501	Advanced Design	ITER Cost Estimating	Hoy	0	0	0	0
	Advanced Design	**TOTAL**		**2979**	**2464**	**2550**	**2550**
AT602010	**Materials Research**	**Materials Science**	Nardella	**7338**	**7043**	**4687**	**4815**
AT60	**Enabling R&D**	**TOTAL**		**28720**	**23737**	**20182**	**20817**

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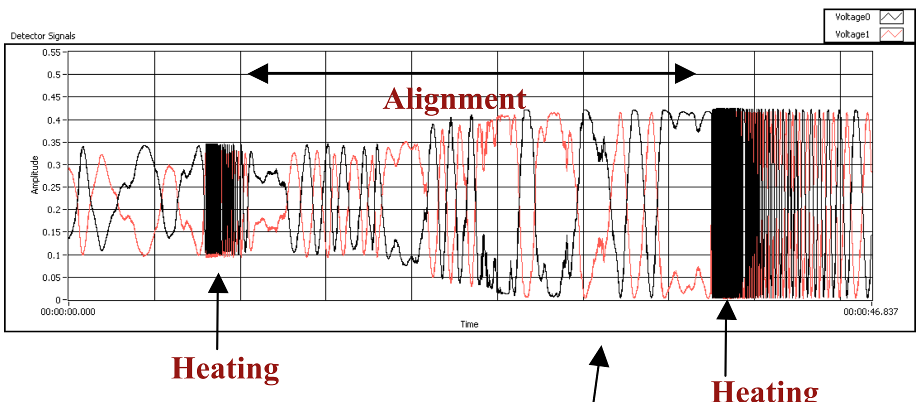
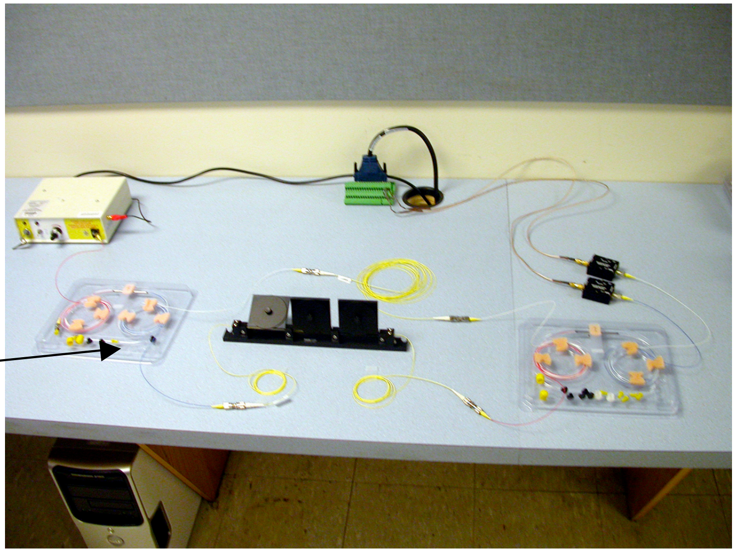
Presentation Format
(for each area/element presenter)

- **FY06/07 Technical Highlights/Accomplishments**
- **Proposed FY08 Tasks of President's Budget**
  List specific tasks with funding and deliverables
- **Proposed FY09 Tasks - Three Categories**
  Tasks with funding and deliverables 10% below FY08 President's Budget level
  2% above FY08 President's Budget level
  Full use of facilities and personnel

Fusion Technology and Engineering FY07 Technical Highlights in Magnet Research

- Base Program work is focused on:
  - Understanding the effects of transverse compression and pure bending on Nb_3Sn through analysis, computation and 3 lab experiments (graduate student research)
  - Development of fiber optic temperature and strain measurement system for superconducting magnets

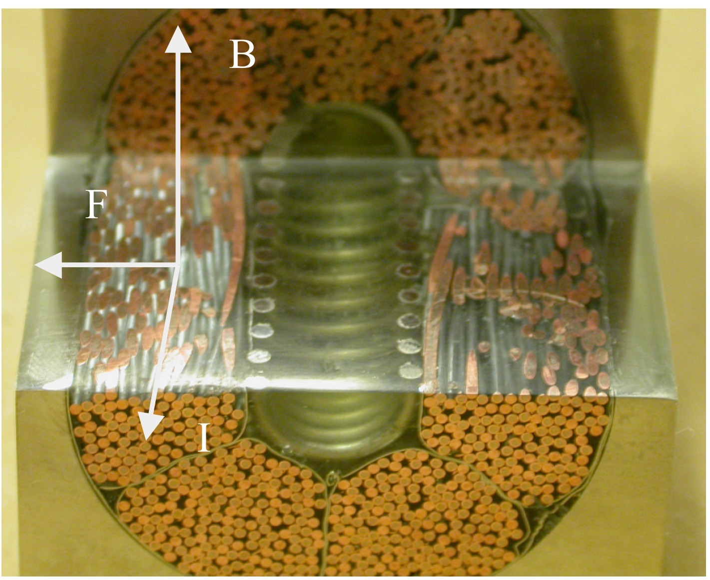


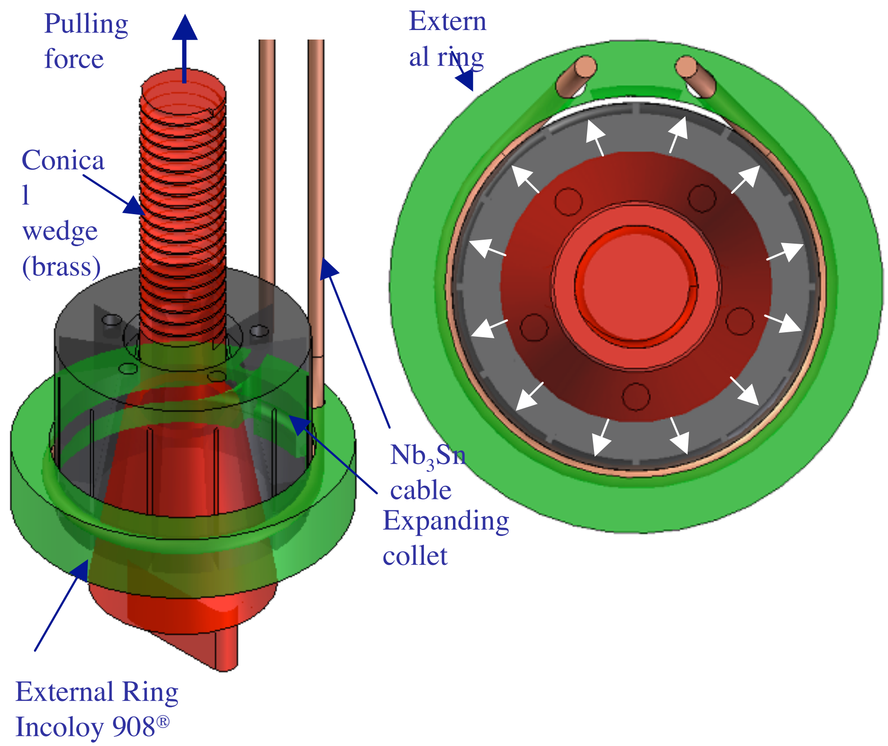


- **Mach-Zender Interferometer**
- **Other devices being developed include:**
  - Brillouin and Raman scattering for thermometry
  - Correlation-Based Continuous-Wave (CBCW) technique for ***rapid*** localized temperature and strain measurements

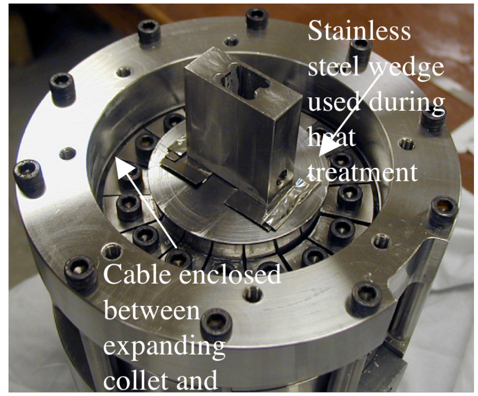
Transverse Compression in a Cable

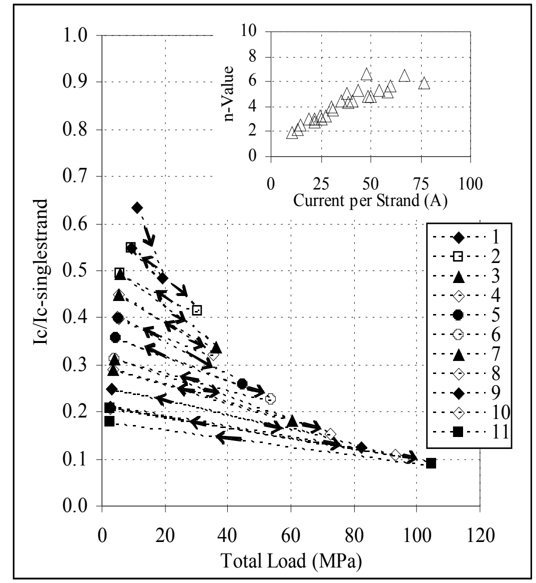
- Apply transverse force on a cable to simulate Lorentz force effect which exists in real CICC
- Maximum external field applicable at NHMFL is 20 T, maximum current is limited to 10 kA but it is NECESSARY to apply extra force to simulate operation conditions

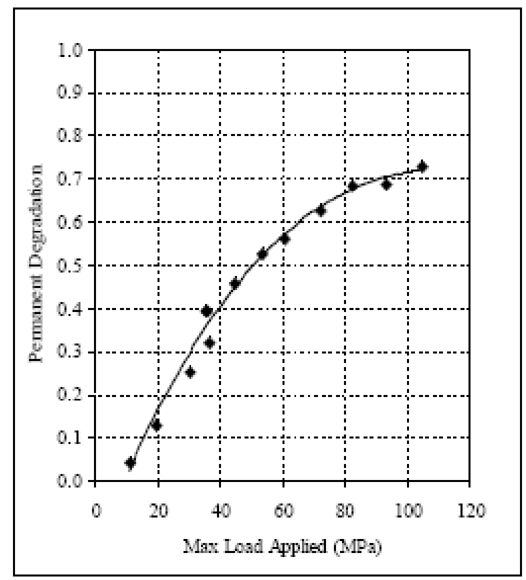




Transverse Compression in a Cable



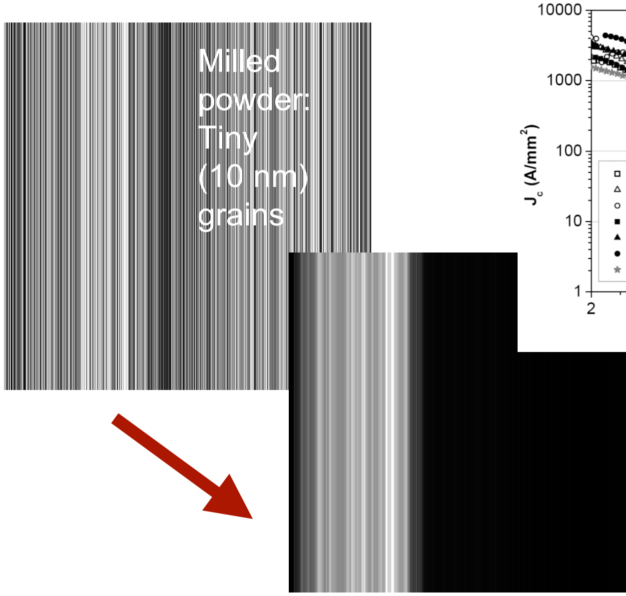




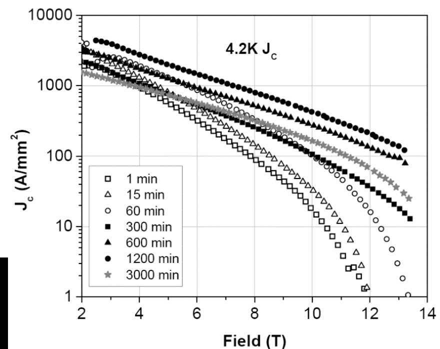
The cable is sensitive to the mechanical load applied (showing *5-10% degradation* for loads lower than *20 MPa*). Even if it partially recovers every time when the load is removed, it always shows a level of *permanent* degradation.

Progress in MgB_2: Next Generation of Superconductor for Fusion – Low cost, high temperature margin (T_c ~35 K), radiation advantages

We have enhanced flux pinning by refining grain size through cold working precursor powders

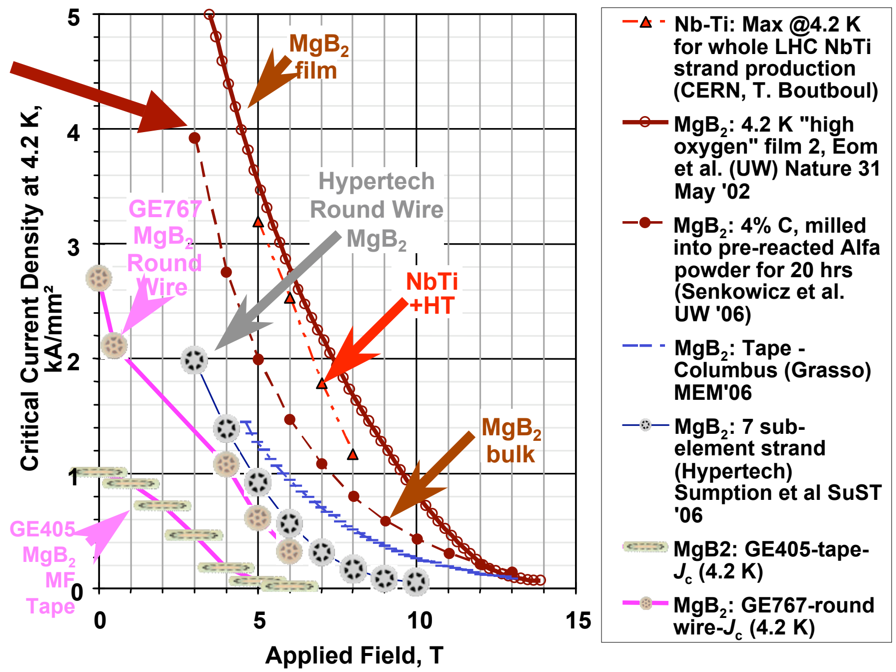


After 1000°C HT, grains still tiny (about 30 nm)



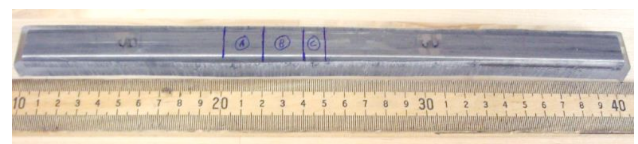
Lots of pinning, High J_c

Recent Advances in MgB_2



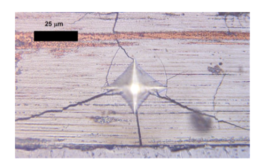
Support for ITER Strand Program

ITER



Epoxy impregnated EFDA Cable for crack metallography as part of ITER strand R&D program.

Nb_3Sn in Compression



Nb_3Sn in Tension

Importance of pre-compression on resistance to Nb_3Sn fracture as shown by micro-hardness measurement

Former DOE-Fusion fellow, Ben Senkowicz has almost completed his PhD. He spent a summer at the Plasma Science and Fusion Center at MIT in 2003 working on crack studies of Nb_3Sn strands. These studies have played an important contribution to the work we are now performing in support of the ITER program.

VLT Magnets FY08/FY09

- **VLT magnets Base Program focused on basic technology R&D and not specifically ITER related**
  - **Superconducting Magnet Development at MIT**
  - **Superconducting Material Development at FSU**

- **Budget Guidance**
  - **FY07 "Ask": \$2000K ⇒ FY07 Congressional Request: \$90 K FSU (supplemented by \$410 K for MIT)**
  - **FY08 Guidance: \$500K: Leads to drastic reduction of base program in FY08 and beyond**
  - **FY09 Guidance: \$500K**
    - **Superconducting Magnet Development (experiments and modeling) - MIT \$410K**
    - **Superconducting Materials Development - FSU \$90K**
- **ITER(USIPO) Magnets funding also reduced for MIT in FY07**
    - **Combined reductions in Base and ITER programs leads to long term loss of core interdisciplinary magnet capabilities (Loss of ~ 6 FTE's and 5 grad students)**
- **Present funding level for magnets is sub-critical**

Guidance level: $410K MIT, $90K FSU

- MgB_2
  - Continued development of MgB_2 as Fusion Conductor
    - Reduction of grain size to improve pinning for J_c
    - Understand and improve grain-to-grain connectivity
  - Apply developments to multifilamentary strand.
  - Provide Superconducting Conductor-relevant materials support for Fusion Community applications
- Superconducting Magnets
  - Continued characterization of transverse stress degradation in Nb_3Sn depending on FY08 results
  - Integration of Fiber Optic temperature and strain sensor in laboratory scale coil and test
  - Incorporation of self-consistent J_c as a function of both longitudinal and transverse strain into magnet design codes

FY2009-Additional Tasks for "Full" Funding

Full Funding Level: $1000K MIT, $200K FSU

- Superconducting Materials
  - Hire Post-Doc in addition to graduate student position
  - Provide material and technical support for post-doctoral study on advancing MgB_2 strand.
  - Apply background in fracture mechanics of ITER Nb_3Sn strand to MgB_2 strand behavior
- Superconducting Magnets
  - Hire Post-Doc, add 1 research staff member and add 3-4 graduate students
  - Restore effort in development and characterization of advance, high strength structural alloys
  - Begin program in adapting HTS 2nd generation superconductor to advanced magnet designs as guided by ARIES studies
    - Include development of demountable joints for superconducting magnets in an advanced fusion machine (tokamak or other)
  - Procurement of relevant materials for HTS and structural studies, along with consumables and laboratory equipment upgrades.
  - Add advanced Nb3Sn wire stability studies

VLT PROGRAM ELEMENT: Magnets

	FY08 (K$)	FY09 (K$)		
	CBR	-10%	2%	Full
Task Descriptions				
Superconducting Magnet Development (Expt. & modeling)	410	369	418	1000
Superconducting Materials Research	90	81	92	200
TOTALS	500	450	510	1200

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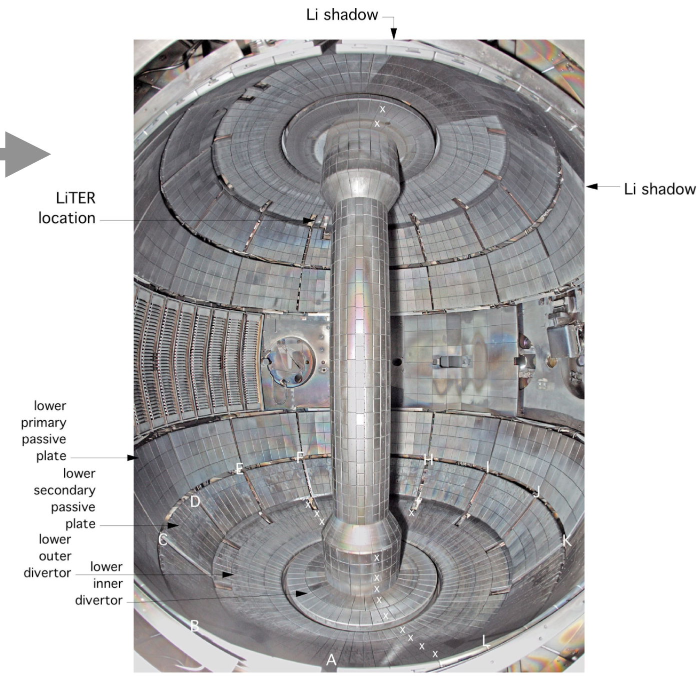
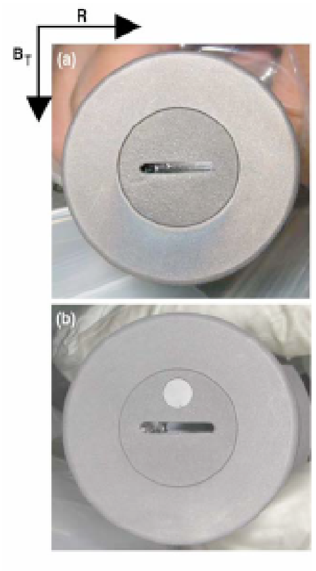
FY07 PFC Accomplishments

Experimental results

- **From ion beam analysis of NSTX tiles: (a) Li remains near surface of graphite; (b) there appears to be no correlation between D and Li coverage.**
  (Sandia, NSTX Team)



- **Modest rise in temperature reduced surface deposition and D concentration inside gap by ~10, data for ITER (DiMES – GA/UCSD/SNL/ANL)**



- **Scaling law to predict mixed-material effects at the ITER divertor plate based on PISCES-B results and validation of plasma-materials interaction models**
  (UCSD/EU collaboration, UCSD/ANL/LLNL)

FY07 PFC Accomplishments

Facilities – upgrades/additions

- **PMTF:**
  - small e-beam (EB60) upgrade to 60kW system with recovered gun, grid control and power supply
  - hydraulic (water flow) test stand for ITER shield/FW
  - thermal cycling test stand for joint QA *(Sandia)*
- **PISCES:** Commissioning of ELM simulation laser system *(UCSD)*

Modeling and Simulations

- Mixed-material sputtering and mixing for ITER *(ANL/LLNL)*
- Experiment/simulation on flow-coupled, wide channel, fast flowing liquid metal LM in divertor-scaled magnetic field *(thesis, UCLA)*

PFC FY08 Major Plans

- PFCs
  - US & foreign ITER FW (Be) Quality mockup tests in PMTF
  - ITER ELM simulations in PISCES, impact of H in surface
  - Develop He-cooled FW and structure for US TBMs
- Plasma Materials Interactions Exp.
  - Analyze NSTX tiles, codep., behavior of Li on surface
  - Examine codeposition in DIII-D and methods (e.g., oxygen bake) to reduce or remove codeposited material
  - Mixed-material experiments in PISCES, D+He+Ne plasmas
  - C deposition and D concentration versus temperature
  - Wall material samples MiMES exposure
- Plasma Materials Interactions Model
  - Analyze time-dependent “blob-like” plasma fluxes to ITER PFCs

PFC FY09 Major Plans

- **PFCs**
  - PMTF upgrade for US ITER wall panel testing
  - Simulate ELM ablation plume transport in PISCES
  - Compare thermal/fluid and stress modeling of modified TBM with initial test results on small mockups

- **Plasma Materials Interactions Exp.**
  - Continue program of analysis of NSTX and DIII-D tiles
  - Mixed-Material experiments for JET/ITER
  - C deposition and D concentration versus temperature in DIII-D
  - Wall material samples MiMES exposure in DIII-D

- **Plasma Materials Interactions Model**
  - 4D kinetic code evaluation of high energy plasma fluxes to PFCs
  - Simulate free surface liquid metal divertor behavior in NSTX; compare with initial NSTX results

VLT PROGRAM ELEMENT: Plasma Facing Components

Task Descriptions	FY08 (K$)		FY09 (K$)		
	CBR		-10%	2%	Full
Solid Surface PFCs (Expt. & modeling)	1,405		1265	1433	2783
Liquid Surface PFCs (Expt. & modeling)	535		482	546	546
Plasma Materials Interactions Expts.	2,325		2093	2372	2682
PMI Modeling	1,140		1026	1163	1568
TOTALS	5405		4866	5514	7579

Scope of Plasma Chamber System Activities

1. ITER Test Blanket Module (TBM) program

- Active participation in the ITER Test Blanket Working Group (TBWG) and advisement to Ad-Hoc Group (AHG), and other advisement as needed.
- Develop TBM test plan, engineering scaling and design interface in collaboration with ITER partners.

2. Predictive capabilities & tools needed by elements of fusion program

- Improve/maintain our predictive capabilities in the areas of neutronics, activation, neutron-material interactions, heat transfer, fluid mechanics, thermo-mechanics, MHD, tritium recovery and control, fuel cycle dynamics, reliability and availability – including development of coupled physics simulation tools.
- Advance understanding and train new generation of scientists in fusion nuclear technology and plasma chamber systems
- Provide support for IEA research tasks, ITER device, other future devices.

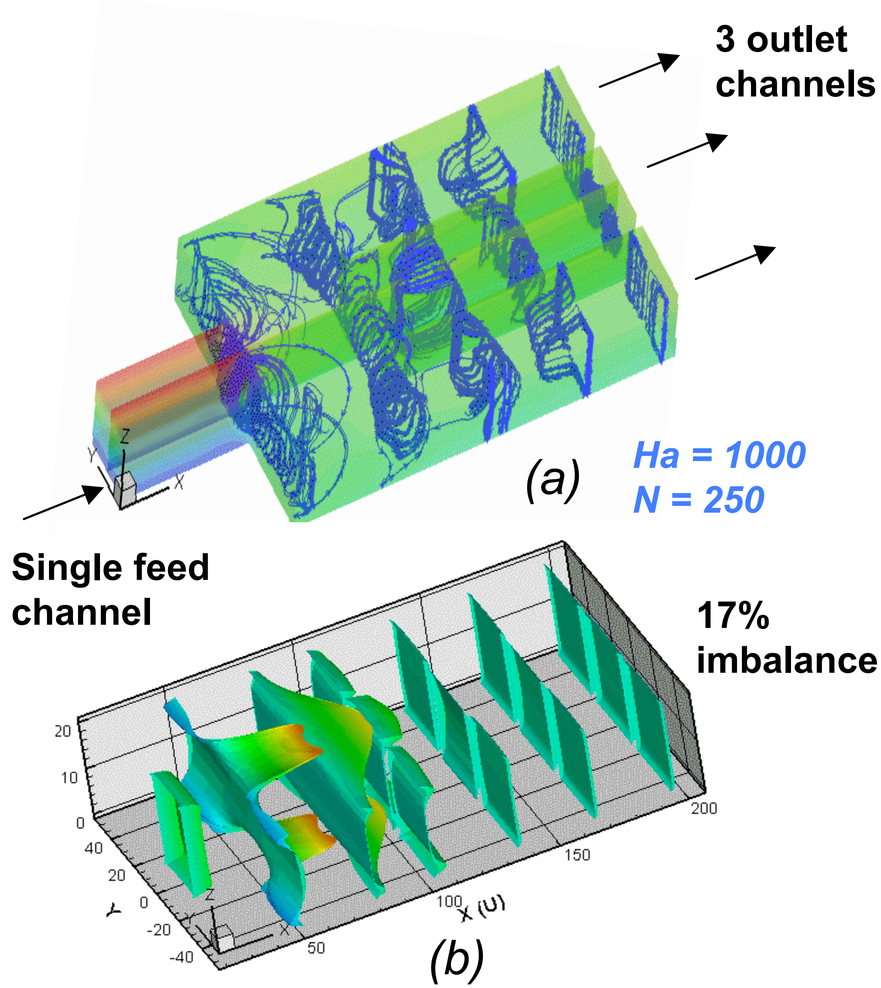
3. TITAN, JUPITER-II

- Complete existing collaboration JUPITER-II, complete negotiation and initiation of new Japanese collaboration TITAN.
- Enhance and focus current international collaborative R&D to provide data for ITER TBM.

Plasma Chamber System

FY07 Accomplishments ($1490k)
Examples:

- ❑ Completed US ITER TBM Technical Planning and Costing Report and Review for proposed TBM Program, per DOE request (with input from other technology program elements)
- ❑ Performed 1st 3-D full MHD simulations of LM flow through complex flow elements of the DCLL. (Shown right – MHD Flow through Manifold. Results indicate a 17% imbalance at ITER relevant characteristic magnetic interaction N)
- ❑ Negotiated and initiated TITAN (formerly JUPITER) collaboration with Japanese MEXT with a strong emphasis on TBM relevant blanket issues (in concert with other technology program elements)
- ❑ Established computational procedures for an integrated thermo fluid and structural thermal stress analysis using a three dimensional CAD TBM model, as an example of the paramount role of Computer Aided Engineering (CAE) in a complex TBM design.



3D simulation of liquid metal flow through a manifold section (a) Electric Current Loops, and (b) Velocity Profiles

Plasma Chamber System

Planned FY08 Accomplishments ($1540k)

Examples:

- ❑ Complete establishment of ITER test blanket program framework by providing US TBM design and preliminary analysis needed for ITER licensing document, and analysis of necessary resources for ITER interfaces. Continue active participation in TBWG.
- ❑ Continue TITAN collaboration with new experiments on MHD flow control including flow in manifolds and with Flow Channel Inserts
- ❑ Continue research tasks for plasma chamber predictive capability and database
  - Verification and validation of high Hartmann number capability of HIMAG 3D simulation tool
  - Complete framework preparation of the integrated computer aided design multi-field analysis effort for an effective TBM simulation
  - Initiate small scale lead-lithium handling, contact resistance, and water-interaction experiments

VLT PROGRAM ELEMENT: Plasma Chamber System

Task Descriptions	FY08 (K$)	FY09 (K$)		
	CBR	-10%	+2%	Full
US Contribution to the International Test Program on ITER (TBWG, Testing Goals, Engineering Scaling)	310	310	310	310
TBM Pre-Conceptual Design Analysis	100	-	131	*
Predictive Capability (including IEA and Research Support for ITER , TBM, and VTBM)	540	486	540	1100
TITAN	590	590	590	590
TOTALS	1540	1386	1571	2100

*Full case for TBM pre-conceptual design is covered under the TBM MIE Project

Plasma Chamber TBM Tasks for FY09 Full Funding

- Continue participation in TBWG and TBM research program planning with emphasis on scientific collaborations, TBM utilization, and Engineering Scaling of phenomena
- Predictive Capability
  - LM MHD Simulation capability development (IEA)
  - Tritium transport and control modeling (IEA)
  - Integrated blanket behavior simulation capability development (Virtual TBM)
  - Small scale experiments with PbLi interactions and FCI materials
  - Solid Breeder Pebble/Pebble Bed effective property characterization (IEA)
  - Thermo-mechanical response of solid breeder/structural material systems (IEA)
- TITAN Experimental Tasks:
  - LM MHD flow control experiments (TITAN) – Insulation techniques and effectiveness, FCI

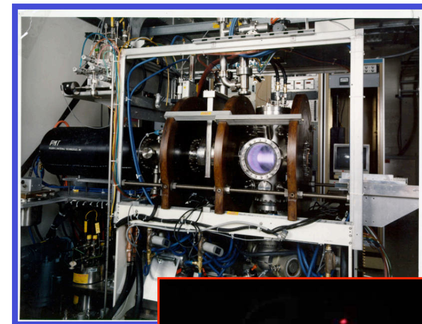
US ITER Test Blanket Module (TBM) MIE Project

- The TBM team has been engaged during the past year in developing strategy, technical plans, and cost estimates for US participation in ITER TBM. A draft report has been prepared. Reviews by the community and costing experts were very helpful and positive.
- About $6.8M of new resources are needed in FY09 to support the recommended TBM baseline scenario.

Tasks	FY09 ($K)
Administration/Integration	700
Engineering design/analysis activity	2200
R&D	3300
• Aggressive RAFS fabrication development	
• SiC FCI development and testing	
• TBM diagnostics and attachment development	
• FS/Be joining	
• He flow distribution and manifold testing	
• Planning and design of needed test facilities	
Licensing, safety, and regulatory support	600

Safety, Environment, and Tritium

FY-07 Main Accomplishments ($ 2280 K)



- Participated as the US member of the ITER safety and licensing working group
- Safety analysis codes MELCOR and TMAP selected by ITER and used to evaluate potential accident scenarios for ITER Preliminary Safety Report (RPrS)
- Tritium retention studies in carbon-fiber composites (CFC) and tungsten (W) were performed in TPE, providing data for fuel retention during ITER long pulse operation
- Safety and failure modes and effects analyses were completed for the US ITER TBM design
- Tritium permeation measurements were obtained for Flibe, completing the JUPITER-II research program
- Dust mobilization and transport models were developed and tested
- Participation initiated in TITAN research program in the areas of tritium retention, permeation, and extraction for fusion systems

Safety, Environment, and Tritium (continued)

FY-08 Planned Accomplishments ($ 2322 K requested)

- **In-vessel Tritium Source Term:**
  - complete test series for Be on W
  - continue testing with CFC and Be on CFC
  - initiate fixture design for TPE testing of tritium permeation in ITER-related compound structures (bonded interfaces)
- **Dust Source Term:**
  - perform chemical reactivity experiments for dust in grooves
  - investigate detection/removal methods suitable for ITER dust limit compliance
  - develop dust mobilization model for ITER accident scenarios
- **TITAN Collaboration:**
  - measure tritium deposition profiles in W exposed to TPE plasma
  - perform tritium solubility measurements in PbLi at low T partial pressure
  - prepare tritium permeation analysis system for handling irradiated samples
- **Fusion Safety Codes, Magnet Safety, and Safety Support:**
  - begin safety analyses for the ITER final design
  - begin verification and validation activities in support of ITER Final Safety Report
  - upgrade arc behavior model in magnet safety code
  - evaluate fusion systems component failure analysis for safety and economic impact
  - support US ITER TBM program and ARIES advanced design studies by providing safety analyses and design feedback

Safety, Environment, and Tritium (continued)

FY-09 Plans ($ 2368 K target)

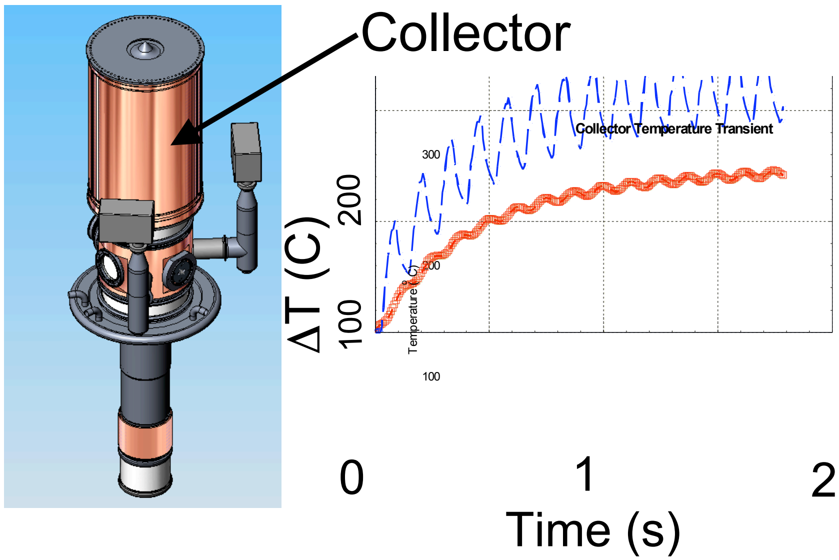
- **In-vessel Tritium Source Term:**
  - complete testing with CFC and Be on CFC
  - fabricate fixture and initiate tests for tritium permeation in ITER-related compound structures (bonded interfaces)
  - test effectiveness of permeation barriers developed to TBM applications (e.g. graded SiC)
- **Dust Source Term:**
  - perform chemical reactivity experiments for dust composed of mixed materials
  - demonstrate detection/removal methods suitable for ITER dust limit compliance
  - apply dust mobilization model for ITER accident scenarios, evaluate explosion potential and mitigation methods
- **TITAN Collaboration:**
  - measure in-situ plasma-driven permeation parameters for W and W-coated RAFS in TPE
  - perform tritium transport measurements at low T partial pressure for RAFS
  - initiate tritium permeation tests on irradiated samples in TPE and the pressure-driven system
- **Fusion Safety Codes, Magnet Safety, and Safety Support:**
  - continue safety analyses for the ITER final design
  - continue verification and validation activities in support of ITER Final Safety Report
  - perform magnet safety assessments with upgraded models
  - evaluate personnel safety issues based on the ITER final design
  - support US ITER TBM program and ARIES advanced design studies by providing safety analyses and design feedback

VLT PROGRAM ELEMENT: Safety, Environment, and Tritium

Task Descriptions	FY08 (K$)	FY09 (K$)		
	CBR	-10%	2%	Full
In-vessel Tritium Source Term	734	734	735	735
Dust Source Term	224	126	224	240
TITAN Collaboration	195	195	195	195
Fusion Safety Codes	734	734	734	735
Magnet Safety	75	0	100	150
Risk Assessment and Safety Support	360	300	380	500
TOTALS	2322	2089	2368	2555

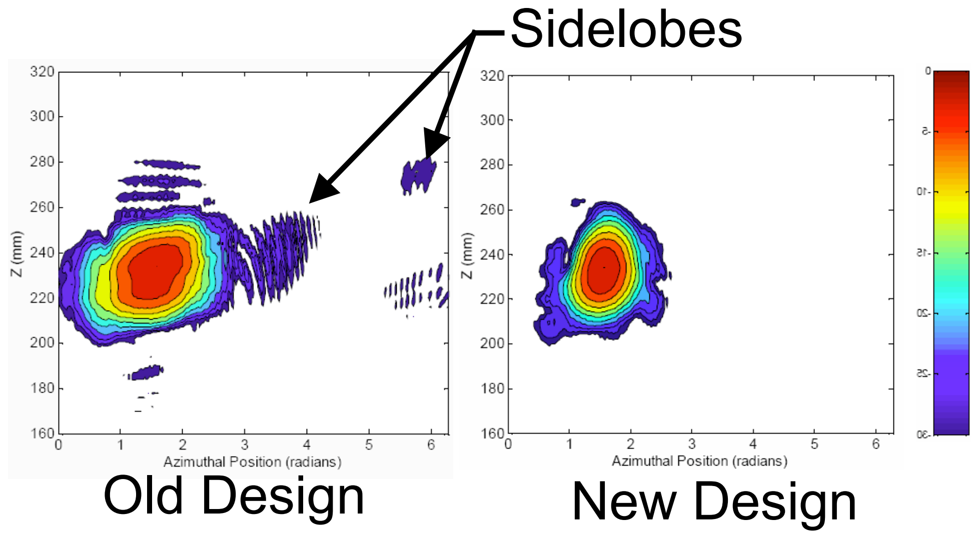
FY07 ECH Technology Advances

Gyrotron Reliability: Improved design of collector



- Improved Collector Lifetime based on analysis by CPI and GA including eddy currents
- Collector life testing in 2007 and 2008 at GA

Gyrotron Efficiency: Improved Internal Mode Converter



- New design eliminates sidelobes
- Gyrotron efficiency ↑ by 9 %.
- Design by Calabazas Creek Research (SBIR) and UW
- To be tested at UW / MIT in ‘08

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FY08 ECH Technology Program

- Advanced, low loss **Transmission Line** components
  - Research on advanced concepts for reducing losses; helps ITER.
- **Experimental Gyrotron Research** on advanced gyrotrons, to demonstrate high efficiency (up to 65%) and > 10% frequency tunability.
- Conduct a vigorous, pioneering program of research on **Modeling / Code Development** to provide advanced design tools for future transmission line and gyrotron development.

- **Major Problem: Industrial Gyrotron Development and Gyrotron Reliability Studies at CPI are terminated.**
  - Supplemental FY06 Funding ends in FY07
  - Very major loss to US enabling technology programs.
  - No CPI support for 6 MW ECH system at GA
  - Highly visible termination of world leading effort.

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FY09 ECH Technology Program

- **Target FY09 Funding Case (+2% vs. FY08):**
  - Continue development of ECH technology from FY08 into FY09
- **10% Reduction Funding Case:**
  - Reduce funding except for transmission lines
- **Full Funding Case - Restore Funding to FY05 Level of $1415k.**
  - Restore industrial development (CPI) program (+$545k)
    - Gyrotron reliability studies
    - Tunable (95 to 115 GHz) 1.5 MW gyrotron for DIII-D

VLT PROGRAM ELEMENT: ECH Technology

Task Descriptions

	FY08 (K$)	FY09 (K$)		
	CBR	-10%	2%	Full
Transmission Line Research	276	266	292	350
High Efficiency / Tunable Gyrotron Research	360	300	360	360
Modeling & Code Development	160	150	160	160
Gyrotron Reliability Studies and Development at CPI	0	0	0	545
TOTALS	796	716	812	1415

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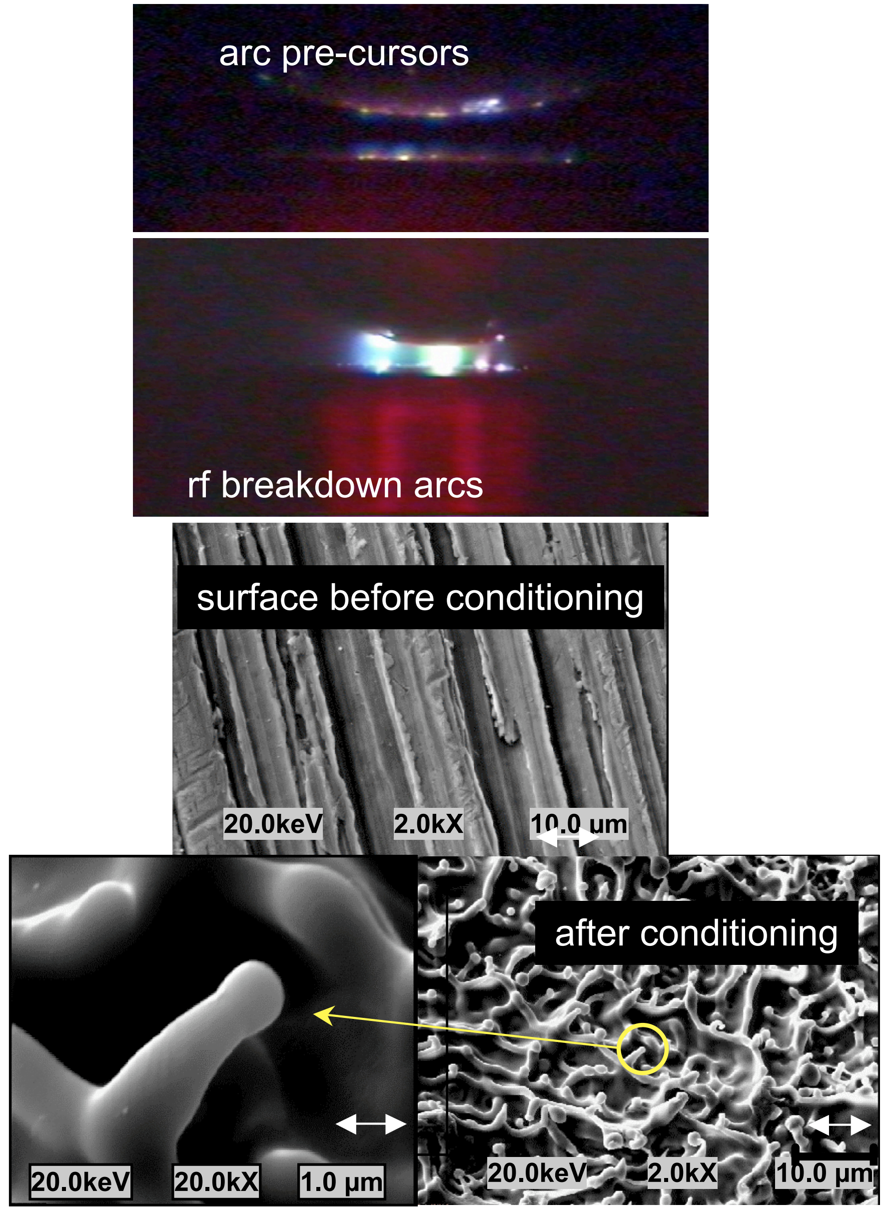
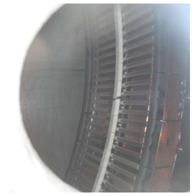
RF Research and Development

- FY-07 Accomplishments ($1570 K)
  - Evaluated post-irradiated ITER candidate ceramics for enhanced RF losses
  - Predictions of edge propagation and antenna spectral models led to improved low-$k_{||}$ HHFW heating on NSTX.
  - Accuracy of mode conversion efficiency measurements was improved by reducing the spot size of EBW emission radiometers.
  - RF breakdowns and arc precursor conditions were characterized as a function of gas pressure and magnetic field using the HV breakdown test stand (ORNL & UIUC).
  - Initial commissioning of load-tolerant antenna on JET
  - Designed edge density reflectometer for installation on C-Mod.
  - Refurbishment and operation of the DIII-D Fast Wave transmitters and antennas.
  - Preparation of test facilities for ITER ICH transmission line and tuning system



RF Research and Development

- FY-08 Planned Accomplishments ($1520 K)
  - **RF Component Development:** Compact inductive and capacitive tuning and pre-tuning elements and cw transmission line components for ITER and DIII-D
  - **High Power Density Antenna Development:** Operate and evaluate the JET-EP antenna, conceptual design of long pulse, low voltage antenna for DIII-D and model ITER coupling physics



JET-EP antenna

  - **Improve Control, Reliability, Protection and Operation of ICH on Fusion Facilities:** Flexible and reliable control systems and matching networks for NSTX, DIII-D, MST and ITER
  - **RF-edge Interactions:** Modeling and diagnostics/experiments on fusion facilities with arc detectors, probes and refectometers on NSTX, DIII-D, C-Mod and ITER
  - **RF Breakdown Studies:** Plasma, UV, and surface material effects on RF and DC breakdown thresholds (at ORNL and University of Illinois facilities)
  - **Innovative Approaches to Advanced Heating & CD for New Concepts:** EBE -> EBW heating for STs and stellarators examine LHCD and RF wall cleaning for ITER.

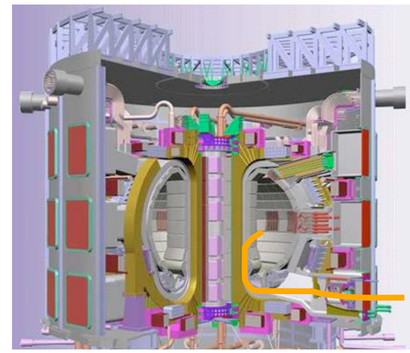
- FY-09 Planned Accomplishments ($1550 K)
  - **RF Component Development:** Compact inductive and capacitive tuning and pre-tuning elements and long pulse components
  - **High Power Density Antenna Development:** JET-EP antenna operation, long pulse, low voltage antenna design.
  - **Improve Control, Reliability, Protection and Operation of ICH on Fusion Facilities:**
  - **RF-edge Interactions and HV Breakdown Studies**
  - **Innovative Approaches to Advanced Heating & CD for New Concepts**

VLT PROGRAM ELEMENT: ICRF Technology

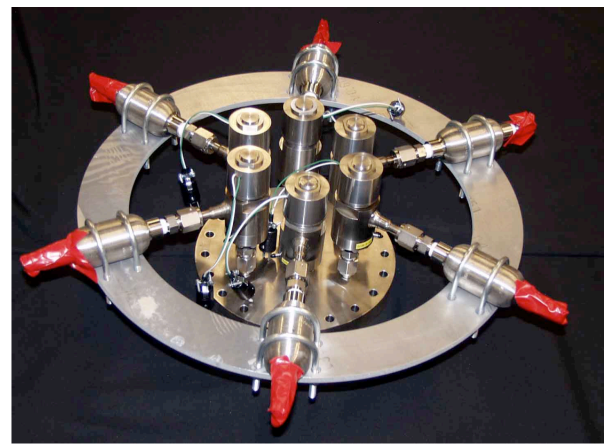
Task Descriptions	FY08 (K$)	FY09 (K$)		
	CBR	-10%	+2%	Full
RF component development	300	290	300	300
High power density antenna development	500	390	475	600
Improve ICRF reliability on fusion facilities	200	190	225	225
RF Edge interactions & diagnostics	200	190	215	215
RF Breakdown studies	155	145	170	185
Advanced heating and CD for new concepts	100	100	100	125
University Programs	65	65	65	70
TOTALS	1520	1370	1550	1720

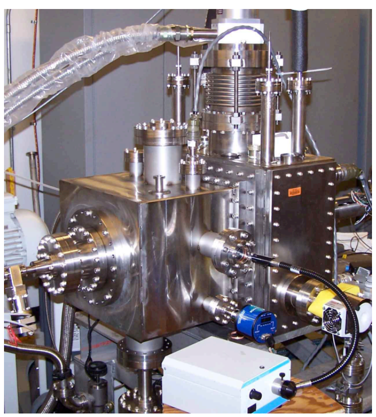
Fueling Development

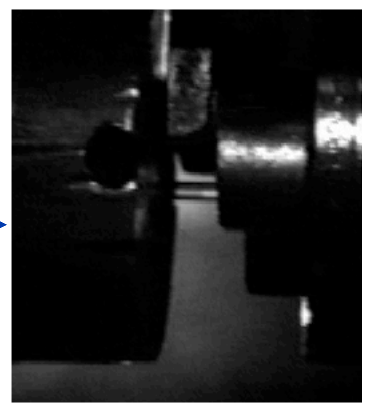
- FY 06-07 Accomplishments
  - Tests of pellet survivability in pressurized ITER guide tube - simulates steady state conditions
  - ITER D/T pellet injector concept development
  - Flexible pellet injector and pellet plasma diagnostics for MST fueling and transport studies
  - Modeling of ITER fueling scenarios
  - High throughput “Medusa” fast valve for massive gas puff disruption mitigation
  - Design and fabrication of pellet dropper ELM-triggering device for DIII-D



ITER Pellet Guide Tube



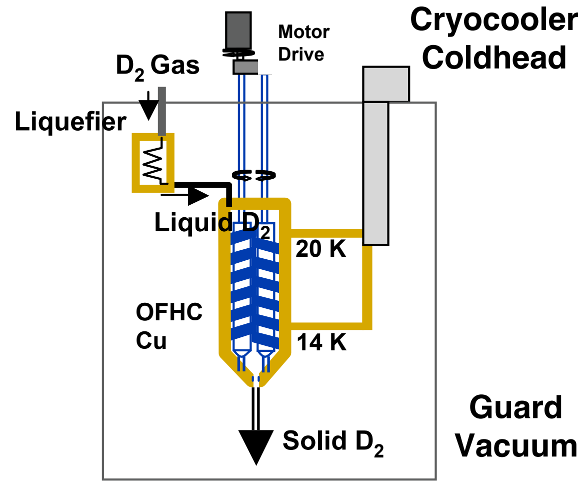




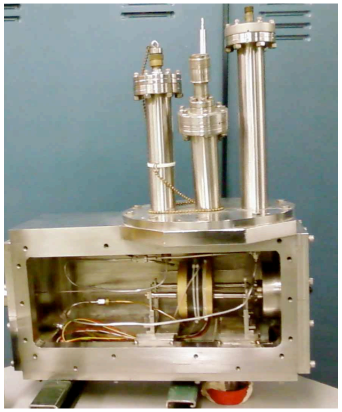
1-mm solid D_2

Fueling Development

- FY 07-08 Planned Accomplishments
  - **High throughput pellet formation:** Prototype continuous deuterium twin screw extruder testing (ITER)
  - **Deep pellet fueling:** Test compact two-state gas gun injector up to 3 km/s
  - **ELM mitigation:** Evaluate pellet dropper and pellet pacing for ELM mitigation (DIII-D, JET)
  - **Disruption mitigation:** Develop/evaluate pipe-gun killer pellet (DIII-D, C-Mod)
- FY 09 Plans
  - **Pellet acceleration:** ITER low gas throughput propellant valve
  - **ELM mitigation:** Improve/evaluate pellet dropper and pellet pacing for ELM mitigation
  - **Disruption mitigation:** Optimize killer pellet/gas jet technology
  - **Fueling and transport tools for alternates:** Implement pellet injection on low wall recycling (lithium) devices

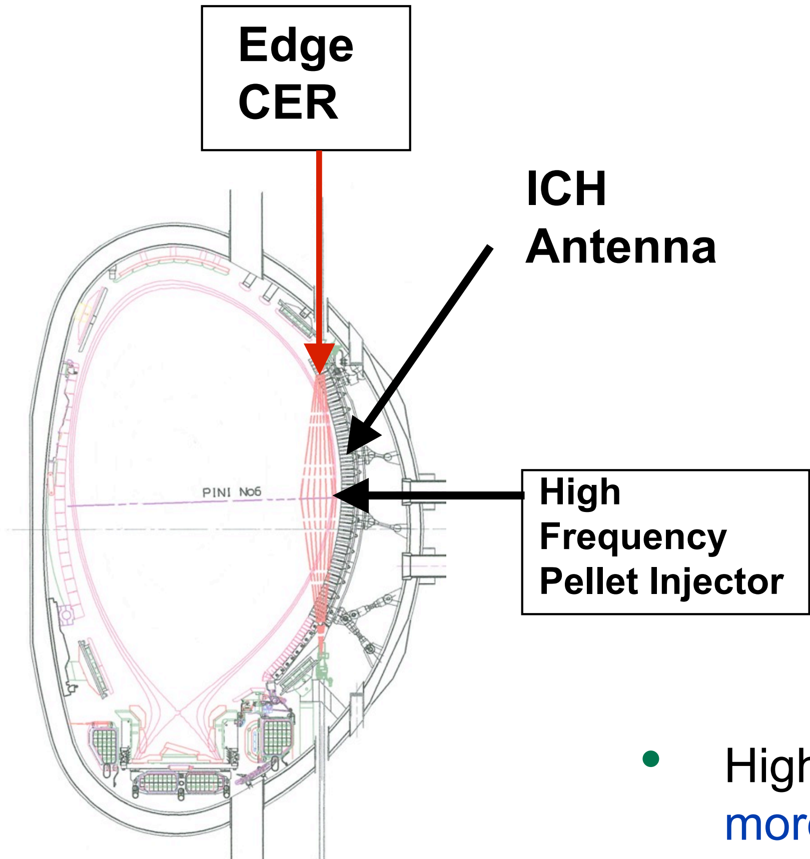


Continuous Extruder



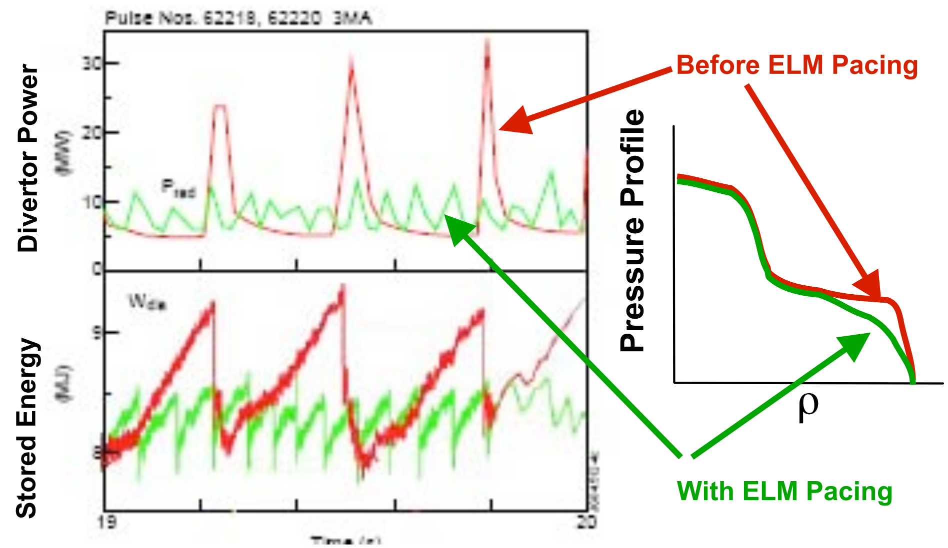
Pipe-Gun Pellet Injector

ELM Mitigation via Pellet Injection and Extrapolation for ITER



JET plan for ELM Mitigation with high frequency pellets and ORNL edge CER

DIII-D to use pellet dropper



4 Hz ELMs on JET are BIG,
20 Hz ELMs are tolerable

J. Pamela et al., 20th IAEA (2004) OV/1-2

- High freq ELMs from Pellet Pacing results in more favorable edge conditions
  - Reduced Heat flux to divertor
  - Increased ICH plasma loading stability
- Physics Interpretation from JET and DIII-D and ITER Extrapolation

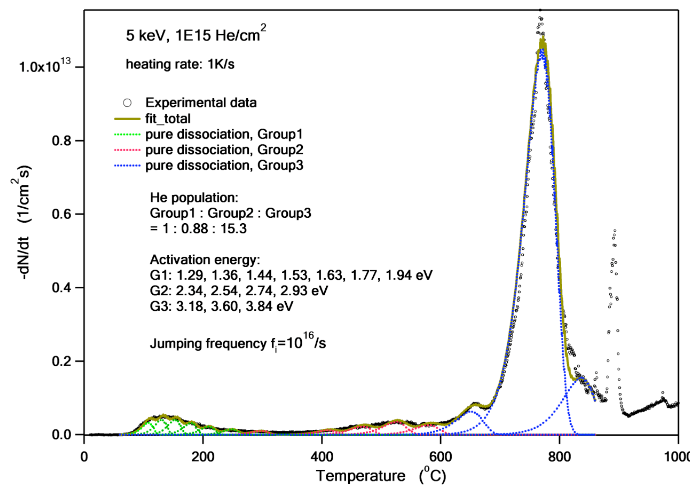
VLT PROGRAM ELEMENT: Fueling and Pumping

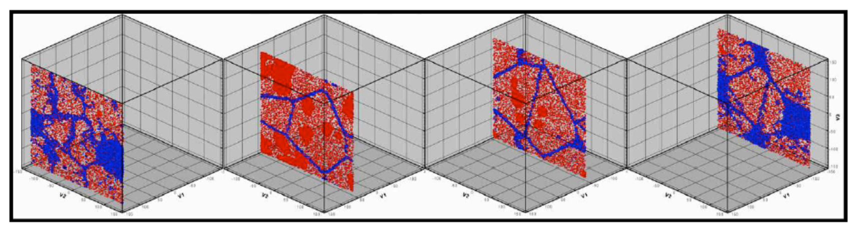
Task Descriptions	FY08 (K$)	FY09 (K$)		
	CBR	-10%	2%	Full
High througput extrusion development	200	180	210	210
High throughput injector development	160	150	165	185
Deep fueling injector development	50	50	50	50
ITER guide tube tests and optimization	50	50	50	50
ITER fueling scenario modeling	50	50	50	50
Fueling tools for alternate concepts	120	100	120	120
Disruption and ELM mitigation	145	120	145	245
TOTALS	775	700	790	910

Materials Science

- **FY-07 Accomplishments ($4687 K)**
  - Explored properties and behavior of advanced nanostructured ferritic alloys yielding improved creep strength, helium trapping efficiency and point defect recombination.
  - Modeling and experiments revealed key mechanisms of He - defect interactions in ferritic alloys.
  - Completed DOE/MEXT experiment to elucidate effect of trace elements on properties of irradiated vanadium alloys.
  - Developed initial fundamental multiscale model of the brittle to ductile fracture toughness Master Curve in ferritic alloys based on measurements of single crystal arrest toughness.
  - Dose / temperature limit for void swelling of SiC composites better defined by METS experiment.
  - Prepared detailed plans and costs for development of ITER Test Blanket Module ferritic steel fabrication technology and SiC flow channel inserts to mitigate MHD effects in PbLi blankets.

He-defect interactions investigated by thermal helium desorption spectroscopy.





Modeling effects of grain boundaries on phase separation in Fe-Cr alloys.

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Materials Science

- **FY-08 Planned Accomplishments ($4815 K)**

Structural Materials

- **Reduced Activation Materials:** Fundamental research on ferritic steels and SiC composites.
- **DOE/JAEA Collaboration:** Investigate effects of thermomechanical processing, joining, and low dose neutron irradiation on conventional and advanced ferritic steels.
- **DOE/MEXT Collaboration:** Investigate synergistic effects of He, tritium and neutron irradiation on properties of bonded materials and dynamic deformation (irradiation creep) of SiC composites.
- **Advanced Materials:** Continue development and evaluation of nanostructured ferritic alloys, and explore novel methods to improve ductility of refractory metals such as W and Mo.
- **Blanket Materials Engineering (TBM Relevant):** Perform basic R&D on ferritic steel fabrication technologies, flow channel insert development, and compatibility of ferritic steel and SiC in flowing PbLi.

Crosscutting Theory & Modeling

- Multiscale modeling of radiation effects on mechanical properties of materials, with emphasis on effects of helium. Develop large-scale finite element models for ITER test blanket module structural components.

Functional Materials

- **Cu Alloys:** Continue study of radiation effects on *in situ* deformation behavior of Cu alloys.

Neutron Source

- No support for IFMIF development at CBR funding level.

Materials Science

- **FY-09 Planned Accomplishments ($4915 K)**

Structural Materials

- **Reduced Activation Materials:** Continue fundamental research on ferritic steels and SiC.
- **DOE/JAEA Collaboration:** Assess effects of intermediate dose irradiation on constitutive properties of advanced alloys.
- **DOE/MEXT Collaboration:** Continue investigation of the synergistic effects of He, tritium and neutron irradiation on properties of bonded materials and dynamic deformation of SiC composites.
- **Advanced Materials:** Continue development of nanostructured ferritic alloys, ductile Mo. Under full funding examine feasibility of using Nb or Ta alloys for tritium permeation in PbLi blankets.
- **Blanket Materials Engineering (TBM Relevant):** Continue support for basic R&D on ferritic steel fabrication technologies, flow channel insert development, and compatibility of ferritic steel/SiC in flowing PbLi.
- **Joining:** Full funding only - investigate effects of irradiation on joining methods relevant to ferritic steels and advanced nanostructured ferritic alloys.
- **Corrosion/Compatibility:** Full funding only - explore potential for environmentally assisted cracking of ferritic steels in PbLi due to radiation induced segregation.

Crosscutting Theory & Modeling

- Continue multiscale modeling of radiation effects on mechanical properties of materials, with emphasis on effects of helium. Initiate development of high-temperature microstructural evolution and deformation models.

Functional Materials

- **Cu Alloys:** Complete study of radiation effects on *in situ* deformation behavior of Cu alloys.

Neutron Source

- No support for IFMIF development at +2% funding level, small IFMIF effort at full funding.

VLT PROGRAM ELEMENT: Materials Science

	FY08 (K$)	FY09 (K$)		
	CBR	-10%	2%	Full
Task Descriptions				
Structural Materials				
Reduced Activation Materials (Ferritic Steels, SiC)	250	200	250	500
DOE/JAEA - Ferritic Steels	1550	1500	1550	1550
DOE/MEXT - Tritium/Irradiation Synergism	715	700	715	715
Advanced Materials (NFA, Ductile Mo, Nb Alloys)	500	400	600	1600
Blanket Materials Engineering (TBM Relevant)	300	250	300	400
Joining	0	0	0	300
Corrosion/Compatibility	0	0	0	300
Crosscutting Theory & Modeling	1300	1135	1300	1500
Functional Materials	200	150	200	300
Neutron Source	0	0	0	50
TOTALS	4815	4335	4915	7215

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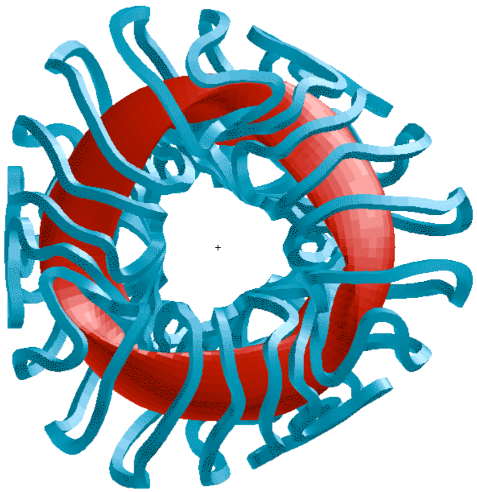
ARIES Compact Stellarator Study is completed (Jan. 2007)

Goal 1: Can compact stellarator power plants similar in size to advanced tokamaks?

- ✓ Compact stellarator power plants can be similar in size (mass) to advanced tokamaks.
- ✓ α particle loss can be reduced substantially
- ✓ Several QA configurations are developed. In particular, relaxing linear MHD stability criteria may lead to configurations with a less complex geometry or coils.



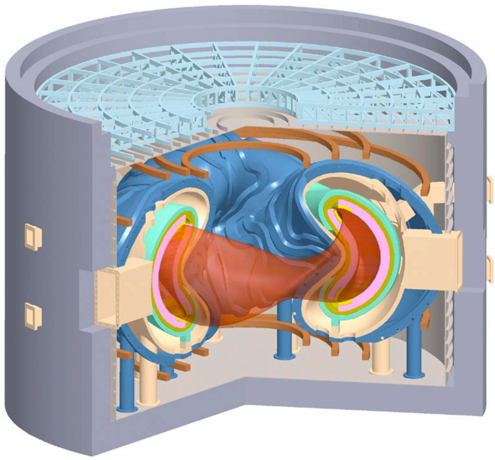
NCSX-Like

MHH2

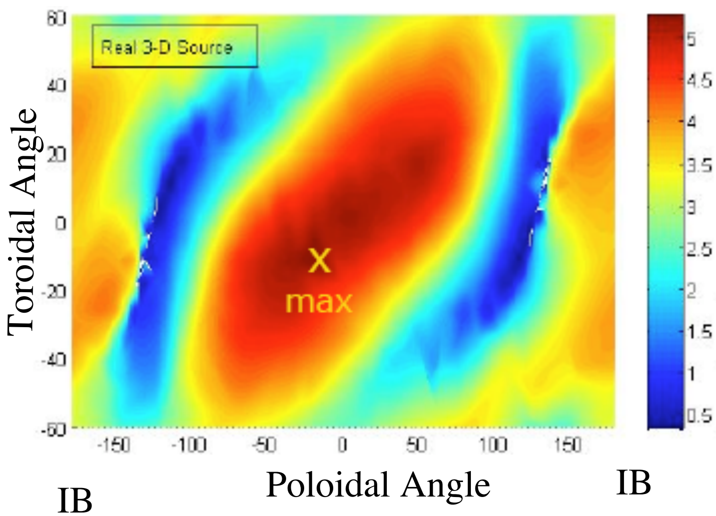
ARIES Compact Stellarator Study is completed (Jan. 2007)

Goal 2: Understand the impact of complex shape and geometry

- ✓ Configuration, assembly, & maintenance drive the design
- ✓ Hardware options are limited because of complexity-driven constraints (e.g., superconducting magnets)
- ✓ 3-D analysis is required for almost all cases (e.g., CAD/MCNP interface for 3-D neutronics, 3-D solid model for magnet support, divertor)
- ✓ Feasibility of manufacturing of component has been included in the design as much as possible.
- ✓ In a large number of cases, manufacturing is challenging and/or very expensive.



Distribution of Neutron wall load



For the next three years, ARIES program will examine "fusion pathways"

- What are the remaining major R&D areas?
  - ✓ What are the data base needed to field a commercial power plant (e.g., licensing, operation, reliability, etc.)?
  - ✓ What it the impact of each R&D item on the attractiveness of the final product.
- Which of the remaining major R&D areas can be explored in existing devices or simulation facilities (i.e., fission reactors)?
- What other major facilities are needed (CTF, Fast track, etc.)
  - ✓ What are the possible embodiments for CTF and what are the their cost/performance attributes.
- We should consider the needs of next-step facilities in the R&D in current facilities as well as initiating R&D needed to ensure maximum utilization of those facilities.

Summary

- The VLT is fully engaged in support of ITER and USBPO activities
  - ITER project R&D (Other Project Costs) dries up in 2010.
- The F08 CBR (3% increase) is a step in the right direction but the budget is still 28% below FY05 levels.
  - Concern for follow on support and full exploitation of ITER
- Full funding case in FY09 restores $7 M of the $8 M shortfall relative to FY05 in the base R&D program (excludes U. S. TBM project)
  - Restores graduate student research in magnets
  - Restores industrial gyrotron research
  - Provide resources to address urgent ITER issues (first wall material choice, disruption and ELM mitigation, heating and current drive mix, etc.)
  - Restores 33% cut in materials research
  - Funds the development of tools to participate in test blanket program
- Additional increment of $6.8 M will provide for start of US TBM program.

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VLT graduate Zinkle is recipient of E. O. Lawrence award.

"Steven Zinkle, a materials scientist, is an expert on the effects of radiation on the properties of materials and has applied this understanding to help establish performance limits of materials in radiation environments. His work has focused on irradiation damage to materials required for nuclear fission and fusion reactors and for space reactor technologies.“

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ITER Project R&D (Other Project Costs) is not a sustainable strategy to long term technology funding

Fiscal Year	Total Estimated Costs (TEC)	Other Project Costs (OPC)	Total Project Costs (TPC)
2006	15.9	3.4	19.3
2007	37.0	23.0	60.0
2008	149.5	10.5	160.0
2009	208.5	6.0	214.5
2010	208.5	1.5	210.0
2011	180.8	.5	181.3
2012	130.0	0	130.0
2013	116.9	0	116.9
2014	30.0	0	30.0
Total	**1,077.1**	**44.9**	**1,122.0**

The European view.

"In parallel the long-term technology programme has been generating the technological knowledge base that should allow Europe to design and operate fusion power plants. Without this accompanying work, JET would probably have not achieved its remarkable success. It is this coordinated effort and integration of the overall Fusion Community which has allowed Europe to lead the world in this field of research.“

Janez Potocnik,
European Commissioner for Science and Research
March 3, 2005 speech at the JET fusion facility

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